

INVESTIGATIONS OF THE IONOSPHERE USING RADIO SIGNALS  
FROM ARTIFICIAL SATELLITES

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## INTRODUCTION

The Radio Research Centre of the University of Auckland was established in 1950, to carry out measurements (for the Post Office and Broadcasting Departments) on the direction of arrival of high frequency radio waves transmitted over long distances. Considerable progress was made in this field, using a new type of rotating interferometer developed by the director, Dr. H.A. Whale. In 1960 NASA initiated a research grant for similar investigations to be carried out on the radio signals received from artificial satellites.

During the following 12 years research extended to include measurements of the elevation angle, amplitude and frequency of satellite signals, to obtain information about the ionosphere and upper atmosphere. New Zealand and its dependencies are particularly suitable for this work since measurements can be carried out over a wide range of latitudes in the southern hemisphere, to complement northern hemisphere studies. During the useful life of the Polar Ionosphere Beacon Satellite (from 1964 to 1970) a chain of 6 recording stations was operated, extending from Rarotonga ( $21^{\circ}\text{S}$ ) to Scott Base ( $78^{\circ}\text{S}$ ). Much new information was obtained on the occurrence and characteristics of irregularities in the ionosphere, at medium latitudes and in the polar regions. With the advent of geostationary satellites equipment was developed to provide a continuous, accurate monitor of the electron content of the ionosphere. This equipment has been widely copied. The records have provided additional information on changes in the ionosphere under quiet and disturbed conditions, and on the occurrence and propagation of atmospheric waves. More recently it has been shown that the records can give a good monitor of neutral exospheric temperature, and of the  $\text{O}^+/\text{H}^+$  ion transition height.

The experimental program was accompanied by theoretical work on the propagation of radio waves through the ionosphere, the analysis of ionograms, and the physics of the ionosphere and exosphere. Partly through this work, new uses for the data are continually appearing. Past records will therefore be of use for many years to come. 45 papers have been published to date, in international research journals, and 5 more based on New Zealand and Antarctic data are planned at present. A survey of the results obtained is given in the following sections, which summarise results from the different papers on each topic. At the end of each major section an assessment is given of the current state and future direction of work in that area. Much of the future work is based on the telemetry station recently constructed in New Zealand for receiving signals from the topside sounder satellites; incorporation of this new information with results from the continuing chain of electron content and ionosonde measurements should considerably increase our understanding of long and short term changes in the upper ionosphere, exosphere and magnetosphere.

1. DIRECTION OF ARRIVAL MEASUREMENTS ON HIGH FREQUENCY SATELLITE SIGNALS.  
(Paper numbers refer to the bibliography at the end of this report, while the dates show when the work described was completed).

- 1.1 *Calculation of electron density profiles from elevation angle measurements on satellites below 300 km (paper 1, May 1961).*

A rotating interferometer, with a 60 ft arm which revolves in 10 seconds, was used to record the bearing and elevation angle of 20 MHz signals from the first satellites. Measurements of the elevation angle of signals received from a satellite below the peak of the *F* layer enable the electron density at the height of the satellite to be calculated directly with an accuracy of a few per cent. The variation of the electron density with height can then be determined up to the peak of the *F* layer. Full allowance is made for the effects of refraction and of curvature of the earth. The results are largely independent of the presence of small irregularities in the ionosphere or of large-scale horizontal gradients.

- 1.2 *Information obtainable from the refraction of satellite signals passing through the ionosphere (paper 5, July 1963).*

Calculations of the refraction suffered by a radio wave passing through a spherically symmetrical ionosphere can be simplified by considering the equivalent flat layer. An effective height for this layer is calculated for parabolic and Chapman layers for a number of different frequencies and angles of incidence. Records of the elevation angle of signals received from an artificial satellite provide the same information as a sweep-frequency virtual height record for signals transmitted vertically through the ionosphere. At large zenith angles, when the ray just penetrates the ionosphere, the measured elevation angles can be used to calculate the scale height of the peak of the ionosphere. At small zenith angles the total electron content of the ionosphere can be determined by a method similar to that used in the analysis of Doppler frequency shift and Faraday fading records. The use of elevation angle measurements has the advantage that fewer assumptions are required in the analysis; the restrictions to line-of-sight propagation with no path splitting are eliminated, while the errors caused by horizontal gradients of ionization are reduced. Elevation angle measurements have the disadvantage, however, that an adequate experimental accuracy is more difficult to obtain.

- 1.3 *Results obtained from the refraction of satellite signals, using the small rotating interferometer (paper 6, July 1963).*

Records of the elevation of the 20 MHz signal from Explorer 7 were used to calculate the scale height at the peak of the *F*-layer, and the total electron content of the ionosphere, over a period of 16 months. The scale height, *H* showed a seasonal variation from 62 km in winter to 77 km in summer, at a mean sunspot number  $\bar{R} = 60$ . The variation with sunspot number in winter was given by  $H = 54(1 + 0.0023 \bar{R})$  km. There was a diurnal variation of about  $\pm 4$  km in summer, but not in winter. The day-to-day variations were about  $\pm 20$  per cent, and were not related to the magnetic activity. The mean scale heights imply a temperature of  $1060^\circ\text{K}$  in winter and  $1320^\circ\text{K}$  in summer, at a height of about 350 km. The solar cycle variation implies a winter temperature of about  $930^\circ\text{K}$  at  $\bar{R} = 0$ , and  $1360^\circ\text{K}$  at  $\bar{R} = 200$ .

The day-to-day fluctuations in the total electron content of the ionosphere, and the sunspot cycle variation, agreed with the variations shown by virtual height records. The ratio of the total content to the peak density in the ionosphere defines an apparent scale height  $H'$  of about 68 km in winter and 82 km in summer. The seasonal variation is only half as large as that shown by similar measurements in the northern hemisphere, suggesting that the world-wide decrease in the critical frequency of the ionosphere in June results from an increase in the temperature of the ionosphere. The difference between the calculated values of  $H'$  and of  $H$ , and a comparison with measurements of the scale height of the lower half of the F-layer, suggests that the scale height increases throughout the F-layer at a rate of about 0.2 km/km.

#### 1.4 *The equivalence of refraction measurements and group-delay measurements for signals transmitted through the ionosphere (paper 40, April 1972).*

A transmission ionogram gives the group delay for radio pulses transmitted vertically through the ionosphere, as the radio frequency is varied. These virtual height curves may also be produced from fixed-frequency observations on orbiting satellites. Analysis of such records can give the thickness of the peak of the ionosphere, a quantity not readily obtained by other techniques. Using the ground reflection trace on topside ionograms, a rapid two-parameter analysis gives the peak thickness to better than 10 per cent.

#### 1.5 *Ionospheric scale height from the refraction of satellite signals, using a large fixed interferometer (paper 41, April 1972).*

Accurate observations of the elevation angle of arrival of 20 MHz signals from the polar orbiting satellite Beacon-B for a 20 month period have provided transmission ionograms which may be reduced to give  $H_p$ , the scale height at the peak of the ionosphere. Noon seasonal averages of  $H_p$  are 1.35 (in winter) to 1.55 (in summer) times greater than the scale height obtained from bottom-side ionograms. A comparison of scale height at the peak with routine measurements of total content and peak electron density indicates that the  $O^+/H^+$  transition level is above 1000 km during the day but comes down to about 630 km on winter nights. A predawn peak in the overall scale height ( $\propto$  total content/peak density) is caused by a lowering of the layer to a region of increased recombination and is magnified in winter by low  $O^+/H^+$  transition levels. After sunrise in winter and equinoxes the overall scale height is less than the scale height at the peak, implying an outwards flux of ionisation which lasts for about three hours. The summer evening increase in  $f_oF2$  requires both a cooling and a raising of the layer for its occurrence.

#### 1.6 *Future work.*

Ionospheric information can be obtained from the elevation angle, amplitude or frequency of satellite signals. The first measurement has not been pursued extensively elsewhere, because of its greater difficulty. The results in 1.5 could not conveniently have been obtained by other means; however the limit of accuracy (set by irregularities in the ionosphere) has been reached and this technique will not be continued. The method of analysis developed in section 1.4 can be applied to the ground returns on topside ionograms, and this will be investigated as a simple means of obtaining electron content and scale height as a function of latitude.

## 2. THE ANALYSIS OF IONOSPHERIC $h'(f)$ RECORDS.

### 2.1 *The relation between group and phase paths in a non-homogeneous ionosphere* (paper 7, March 1965)

Appleton derived the relation  $P' = P + f \frac{dP}{df}$ , connecting the phase path  $P$  and the group path  $P'$  for a radio wave of frequency  $f$ , for the case of a horizontally stratified ionosphere in the absence of a magnetic field. It is shown that this result is in fact completely general, and can be applied to propagation between any two fixed points in or below any form of ionosphere. It does not, however, hold for the ionospheric section of a path between two fixed points below the ionosphere.

### 2.2 *The analysis of ionospheric $h'(f)$ records using the phase refractive index* (paper 3, August 1962).

The analysis of ionograms can be carried out using the phase refractive index  $\mu$ , instead of the group refractive index  $\mu'$ . This gives a very considerable saving in computational effort. It also yields some increase in accuracy, when the normal linear lamination analysis is being used.

### 2.3 *The effect of collisions on the virtual height and absorption of radio waves in the ionosphere* (paper 12, June 1966).

Calculations for the ordinary ray under different conditions show that the effect of collisions can considerably reduce the virtual heights given by ray theory. This reduction is, however, caused entirely by the errors inherent in ray theory. Phase integral calculations show that the simplest ray theory result, ignoring collisions, is accurate to within 0.1 percent except under those conditions which require a full wave treatment.

Calculations of absorption by integrating the absorption coefficient  $k$  up to the level  $X = 1$  also give incorrect results, because of ray theory limitations. These errors are exactly counterbalanced by the errors in a commonly used approximation for  $k$ . The use of this approximation therefore gives results which are more accurate, by several orders of magnitude, than the use of the exact expression.

### 2.4 *The calculation of the heights of the peaks of the ionospheric layers* (paper 10, May 1965).

The five-point Kelso analysis, for calculating the real height of reflection at any frequency in terms of the virtual heights at five lower frequencies, is compared with a single-polynomial analysis using the same frequencies. The two methods are found to give the same result, to within one part in a thousand, for any virtual height curve.

When used to calculate the real height ( $h_m$ ) at a critical frequency, both methods give a result which is 10-20 km too low. The polynomial method was therefore modified by including a parabolic peak in the assumed form of the real height curve. This reduces the systematic error in  $h_m$  to less than 0.5 km. The same result can be obtained by adding a correction  $C(h_5' - h_4')$  to the Kelso analysis. Values of  $C$  are given for use with five and ten point Schmerling coefficients at dip angles up to 80 degrees.

## 2.5 *Direct manual calculations of ionospheric parameters, using a single polynomial analysis* (paper 13, November 1964).

Two extensions of the basic polynomial analysis are described. Firstly the polynomial representation of the real-height curve is modified to include a parabolic peak; this greatly increases the accuracy of calculations near the peak of the ionospheric layers. Secondly the analytic expression for the real-height curve is used to obtain expressions for the height of the peak ( $h_m$ ) and the scale height at the peak ( $H$ ). Integration of the real-height curve also gives an expression for the effective subpeak thickness of the ionosphere ( $T$ ), defined as the total amount of ionization below the peak divided by the density at the peak. These three expressions are then used to obtain coefficients relating  $h_m$ ,  $H$ , and  $T$  to the virtual heights at any required frequencies.

Eighty-four sets of coefficients are given for analysing  $h'(f)$  records taken anywhere in the world, with critical frequencies between 1.5 and 20 MHz. These coefficients give the values of  $h_m$ ,  $H$ ,  $T$ , and the real heights of reflection directly in terms of the virtual heights at five or six different frequencies. For calculations on a single ionospheric layer the accuracy is extremely high, being equivalent to that obtained with a lamination analysis using more than 50 points. For calculations on the day-time  $F$  layer, coefficients are provided with alternative sampling points chosen to reduce the effects of the  $E$  and  $F1$  layer cusps, so that the height, scale height, and total content of the  $F$  layer can be determined with an accuracy equivalent to a lamination analysis using more than 20 points. Finally, coefficients including an extraordinary-ray correction for the underlying ionization are given, to enable accurate calculations for the night-time  $F$  layer.

## 2.6 *The single polynomial analysis of ionograms* (paper 22, August 1968).

A new formulation of the single-polynomial analysis is presented, in which the electron density profile is assumed to begin with a flat base at a height equal to the lowest measured virtual height. This formulation gives a more accurately defined profile with only a small number of points and agrees with the assumptions normally made. Near the critical frequency the electron density profile is required to approach a parabolic distribution. Coefficients are given for the rapid analysis of ionograms taken anywhere in the world. The height of the peak, the scale height at the peak, and the subpeak electron content, along with five or six points on the electron density profile, are obtained directly from a small number of measured virtual heights.

## 2.7 *The overlapping polynomial analysis of ionograms* (paper 14, November 1964).

A simple and more direct derivation of the equations used in the overlapping-polynomial analysis of ionograms is given. A set of five simultaneous equations is obtained which define the five polynomial coefficients required at each frequency. The steps involved in programming a computer to calculate these coefficients and analyze a virtual-height record are outlined. The calculation of the coefficients takes about 40 percent longer than the calculation of the coefficients for a lamination analysis using the same number of points. Since, however, the polynomial method requires only about one quarter as many points as a lamination analysis for a given accuracy, a considerable saving is achieved both in the time required for measuring the virtual heights and in the computer time required for calculating the

coefficients and analyzing the records. A procedure for allowing for the presence of ionization below the nighttime *F* layer is also described; this includes corrections for both the low-density ionization in the *E* region and the finite ionization gradient at the bottom of the *F* layer.

## 2.8 *A direct analysis of ionograms at magnetic dip angles of 26 to 30 degrees* (paper 45, 1960).

At dip angles of  $26-30^\circ$ , the group retardation of the extra-ordinary ray is a constant (depending on frequency) times the retardation of the ordinary ray reflected at the same true height. The true height can therefore be found directly from the virtual heights of the two rays, with no assumptions about the shape of other parts of the profile. Results for three days show that any valley between the *E* and *F* layers was less than about 15 km wide, from sunrise to sunset. At night the addition of a simple extraordinary ray correction reduces the errors in standard methods of analysis from about 50 km to about 5 km, at frequencies near 2 MHz.

## 2.9 *The relative accuracy of ionogram analysis techniques* (paper 46, July 1973).

Increasing accuracy in the conversion of  $h'(f)$  to  $N(h)$  profiles is obtained by increasing the order of the polynomial used to interpolate between measured points. Linear and parabolic lamination techniques correspond to first and second order interpolation. Fourth order interpolation (as in the 5-term overlapping polynomial method) is about optimum. In comparing different methods, it is essential that fixed boundary conditions be employed; when this is done an adjacent polynomial technique is much less accurate than overlapping polynomials. Possible procedures for reducing the errors caused by underlying and valley ionisation are critically reviewed. It is concluded that only a small number of parameters should be used to specify the 'unseen' ionisation.

## 2.10 *Future work.*

Maximum accuracy is obtained in the analysis of ionograms by the use of overlapping polynomial techniques. If the  $N(h)$  profile is to satisfy, exactly, all the virtual height data, the degree of the polynomial is limited (to 4 or 5) and the number of data points which can usefully be employed is also limited. A least squares analysis has therefore been developed in which high order polynomials can be fitted to very large numbers of virtual height measurements. Incorporation of extraordinary ray data in the least squares fit provides an ideal method for treating the starting and valley problems. The same program can be used for rapid, approximate calculations by fitting a single polynomial to a small number of data points. The procedure also offers considerable advantages for the analysis of topside ionograms, since a profile can be fitted to fragmentary ordinary and extraordinary ray traces. Work is proceeding on the analysis of topside ionograms, obtained in New Zealand, for comparison with bottomside and total content observations.

### 3. STUDIES OF IONOSPHERIC IRREGULARITIES.

#### 3.1 *The field alignment of small ionospheric irregularities* (paper 27, February 1969).

All transits of the satellites BeB and BeC observed over a period of 3 years were examined to find cases when the angle between the ray path and the magnetic field in the ionosphere became less than  $10^\circ$ . The amplitude and polarization scintillations occurring at these times were compared with the scintillations occurring, on the same transits, when the ray path made an angle of  $30^\circ$  to the magnetic field. In general the results showed only a slight tendency to field alignment, with a mean axis ratio for the irregularities of about 2 or 3 to 1. The field alignment is greatest near local midnight, and almost disappears in the afternoon. On 10 per cent of the transits the scintillations increased greatly near the longitudinal point, showing the occasional existence of highly elongated irregularities.

#### 3.2 *The height of large ionospheric irregularities* (paper 9, July 1965).

The amplitude of the 54 MHz signal from the satellite Transit 4A was recorded at two stations, 100 km apart, from March to August 1964. The time difference between observing similar fluctuations in the fading period at the two stations was used to determine the height of ionospheric irregularities. 44 irregularities were observed, predominantly between the hours 0800 and 1800 local time, at heights from 180 to 750 km. The horizontal sizes varied from 75 to 520 km. The denser irregularities occurred only near the peak of the ionosphere, between 250 and 400 km, so that the mean percentage density fluctuations were approximately the same at all heights. Two examples of trains of irregularities were found, in which the irregularities lay on a straight line tilted down to the south at an angle of about 15 degrees. There was some evidence that the individual irregularities were also tilted down to the south by this amount.

#### 3.3 *The diffraction of satellite signals by isolated ionospheric irregularities* (paper 29, January 1970).

Procedures were developed for the rapid calculation of refraction and diffraction patterns produced by isolated ionospheric irregularities. These patterns are observed experimentally, and a sensitive polarisation angle recorder was also used to determine the associated changes in electron content. Large scale irregularities in the F-region are shown to cause variations of several decibels in the amplitude of 20 and 40 MHz satellite signals. Dense, isolated irregularities produce patches of 'scintillations' on 20 MHz. The common assumption that scintillations are caused by a large number of small irregularities, acting as a random diffracting screen, is therefore incorrect on many occasions.

Small isolated irregularities produce diffraction patterns which depend only on the total number of electrons in the irregularity, and the height. Irregularities of all sizes commonly occur in trains; in such cases the height of the irregularities can be determined by comparing the depth of the fluctuations in amplitude and in polarisation. Calculated heights are mostly in or above the F-region. For large isolated irregularities, their position with respect to the peak of the F-layer can be obtained directly from the different times at which amplitude fluctuations occur on 20 and 40 MHz.



### 3.4 *Large scale irregularities in the ionosphere* (paper 4, December 1962).

The amplitude of the 20 MHz signal from the satellite Explorer 7 was recorded at Auckland from November 1960 to August 1961. Variations in the fading period are used to study the irregularities that occur in the electron density of the ionosphere. Relations are given for calculating the size and density of these irregularities directly from plots of the fading period of the received signal. Results for 770 irregularities, observed at all times of day, with sizes from 5 to 500 km, are presented. The number with sizes between  $S$  and  $S + \Delta S$  was approximately proportional to  $\Delta S/S$ . The electron content of the irregularities, measured vertically, was generally between 0.03 and 4 per cent of the total electron content of the ionosphere, with a median value of 0.25 per cent. The density at the center of the irregularities differed from the density of the background ionization by about 1 per cent for the smaller and 10 per cent for the largest ones. The irregularities were not elongated in the direction of the magnetic field, but occurred in the form of horizontal slabs with a vertical thickness equal to about one-fifth of the horizontal dimension. The fact that most irregularities larger than 50 km occurred in series of three or more similar ones suggests that they are caused by a wave of disturbance propagated through the ionosphere with a wavelength of about 100 km.

### 3.5 *The characteristics of large ionospheric irregularities* (paper 17, May 1967).

The period of the Faraday fading of 20 MHz satellite signals was plotted throughout 521 transits of three different satellites, at heights of 200-1600 km. From these plots the size and electron content of 2650 separate irregularities were determined. The calculated sizes were spread evenly over the observable range from 10 to 400 km. The irregularities were not field aligned, but were flattened vertically with a mean thickness of 0.4 times the horizontal size. They were more common during the day than at night. The number of irregularities observed at any height was proportional to the electron density at that height, suggesting that the percentage changes in electron density are approximately the same at all heights. These changes were generally between 1 and 10 per cent and were independent of the size of the irregularities. The changes in total content, of 0.1-10 per cent, were therefore proportional to size. The mean horizontal gradients in total content were independent of the size of the irregularity and of the time of day.

### 3.6 *Periodic disturbances in the ionosphere* (paper 16, July 1967).

Total electron content measurements, at latitudes of  $34^{\circ}\text{S}$  and  $42^{\circ}\text{S}$ , show that 30 to 50 per cent of all large-scale irregularities in the ionosphere are periodic in space and in time. The observed wavelengths are generally between 40 and 160 km. The periods range from about 60 minutes down to a sharply defined lower limit of 15 minutes. This agrees precisely with the spectrum for gravity waves in the  $F$  region. Periodic disturbances did not occur near sunrise and sunset. Daytime disturbances caused periodic changes in total content of a few per cent, and were present for about 5% of the time at the lower latitude in summer. They became more common at the higher latitude and in winter, when the ionosphere was continually disturbed by the passage of large irregularities. Most of these had periods of about 20 minutes, suggesting a thermobaric resonance in the  $F$  region. Nighttime disturbances were generally more intense and occurred most frequently at the lower latitude in summer.

### 3.7 *Non-periodic disturbances in the ionosphere* (paper 35, January 1971).

Continuous records of the electron content of the ionosphere at latitudes of  $34^{\circ}\text{S}$  and  $42^{\circ}\text{S}$  show both periodic and isolated (nonperiodic) fluctuations in approximately equal numbers. Both types have peaks of occurrence near noon and midnight, although the isolated irregularities peak 2 hours before the periodic type. Periodic irregularities predominate in the relatively stable conditions from noon to 4 P.M. and 11 P.M. to 4 A.M., and show a large increase on winter days at high latitudes. Decreases in electron content account for about 16% of the nonperiodic irregularities; these negative irregularities are twice as common near 7 A.M., suggesting localized decreases in the production rate.

### 3.8 *The spectrum of electron content fluctuations in the ionosphere* (paper 36, June 1971).

Continuous records of the electron content of the ionosphere, from 1965 to 1970, are used to obtain power spectra covering periods from 30 sec to 2 yr at latitudes of  $34^{\circ}\text{S}$  and  $42^{\circ}\text{S}$ . At periods up to 5 min, amplitudes were less than 0.2 per cent of the total electron content. Variations produced by gravity waves were very common in the range 20-80 min, with no preferred periods. The r.m.s. amplitude per octave  $A_0$  was about  $10^{15}$  electrons/ $\text{m}^2$ , or 0.6 per cent of the mean electron content. The amplitude increased during the day, particularly in winter when periodic components predominated. The cut-off at about 17 min was sharply defined, giving a mean scale height for the neutral atmosphere (at 300 km) of about 43 km in summer, 47 km on winter days and 42 km on winter nights.

From 12 hr to 1 month  $A_0$  was about 12 per cent of the mean electron content in both summer and winter at  $34^{\circ}\text{S}$ , and 10 per cent at  $42^{\circ}\text{S}$ . The 24 hr and 27 day peaks were largest just before sunspot maximum, and almost disappeared near sunspot minimum. Variations between 1 and 27 days reflect the random occurrence of ionospheric storms and show no consistent peaks. Day to day and night to night variations were both about 10 per cent of the background content for periods from 2 days to 2 yr, apart from a slight decrease between 1 and 6 months.

### 3.9 *A regular disturbance in the topside ionosphere* (paper 23, August 1968).

Continuous records of the electron content of the ionosphere, obtained over a period of several years, have shown that a large disturbance occurs between 10 P.M. and 1 A.M. on about half the nights in summer. After an initial small decrease, the electron content increases rapidly by about 30% and occasionally up to 80%. The increase lasts for 15 to 100 minutes and may be followed by large oscillations. The effects are generally confined to the topside ionosphere, where the electron concentration must fluctuate through a factor of 2 or more. The disturbance consists of an extended wavefront, at latitudes less than  $40^{\circ}\text{S}$ , moving toward the northwest with a velocity of 140 m/sec. The front has a depth of several hundred kilometers and dies out within a few thousand kilometers. There is no relation with magnetic activity, but the occurrence increases with sunspot number.

### 3.10 *Future work.*

Continuous electron content records at a network of stations, with spacings of about 300 km, have been used to calculate the direction and velocity of several thousand irregularities. This work will be published in 1974. It is now established that ionospheric irregularities are generally produced by the passage of internal gravity waves. To study the spectral characteristics in more detail, measurements are currently being obtained on a triangle with 8 km sides. The electron content at each site is digitised and recorded every 10 seconds with a resolution of better than 0.1%. Theoretical and experimental work is also proceeding on the sensitivity of electron content measurements to waves of different types, using drifting geostationary satellites to obtain observations at angles of  $5^\circ$  to  $60^\circ$  to the magnetic field. Topside sounder records, now available over New Zealand, are being used to further investigate the peculiar irregularity of section 3.9, which occurs only at great heights. New measurements planned for the Antarctic should throw more light on the origin of some large travelling disturbances.

## 4. SATELLITE BEACON STUDIES OF THE POLAR IONOSPHERE.

### 4.1 *The use of satellite signals to investigate the polar ionosphere (paper 8, July 1965).*

Research programs at Scott Base ( $78^\circ\text{S}$ ,  $167^\circ\text{E}$ ), Byrd ( $80^\circ\text{S}$ ,  $120^\circ\text{W}$ ) and Wilkes ( $66^\circ\text{S}$ ,  $111^\circ\text{E}$ ) are summarised. The New Zealand measurements at Scott Base consisted of amplitude and polarisation records of the 20, 40 and 41 MHz signals from the Polar Ionosphere Beacon satellite S-66. Equipment was installed in January 1964, and 14 transits were recorded each day until December 1970. Amplitude records provide a sensitive indicator of large and small irregularities; these are far more prevalent in the polar ionosphere than at mid-latitudes. Faraday rotation measurements give information on the total electron content of the ionosphere, and the presence of large horizontal gradients.

### 4.2 *Horizontal gradients in the polar ionosphere (paper 25, December 1968).*

At low and mid-latitudes the Faraday fading rate of satellite signals gives information on the total electron content of the ionosphere. At high latitudes, however, it depends primarily on horizontal changes in electron content. Typical gradients of  $2 \times 10^{10}$  electrons /  $\text{m}^3$  are ten times larger than mid-latitude values. The gradients are larger near the dip pole. There is a marked universal time variation, with a maximum near 0300 and a minimum near 1500 U.T.. The amplitude of this variation increases near solar maximum.

### 4.3 *Irregular regions in the Antarctic ionosphere (paper 24, October, 1968).*

Irregularities are found to occur in patches, with a horizontal extent of about 200 to 1000 km. Observations on successive transits show that the patches can persist for periods of 8 hours. In this time they drift through distances of the order of 1000 km, with velocities of 30 to 100 m/sec. No preferred direction of movement could be detected.

4.4 *The distribution of irregularities in the Antarctic ionosphere near solar minimum (paper 18, April 1967).*

14 transits of the satellite S-66 were recorded at Scott Base ( $78^{\circ}\text{S}$ ,  $167^{\circ}\text{E}$ ) each day from October 1964. The records are scaled to determine the degree of irregularity of the ionosphere at intervals of 0.2 min throughout each transit. By combining the results from 3000 separate transits the mean degree of irregularity of the antarctic ionosphere has been mapped over a large area including the geographic, geomagnetic and dip poles and extending across the auroral zone.

Intense field aligned irregularities were observed for 65 per cent of the time in both winter and summer. The area between the geographic and geomagnetic poles was consistently irregular in both seasons. A weaker irregular region extended along the line  $L = 20$  to include the dip pole. There was a slight increase in the density of irregularities at all points in winter, so that the percentage fluctuations in electron density were twice as large in winter as in summer. A narrow disturbed region at  $170^{\circ}\text{E}$  in winter coincided with a region of increased  $f_0F_2$ . The ionosphere was generally smoother away from the poles, and there was no disturbed region associated with the auroral zone.

4.5 *Diurnal, solar cycle and magnetic activity variations in the occurrence and distribution of irregularities (paper 26, November 1968).*

Radio signals from the satellite S-66 were recorded at Scott Base ( $78^{\circ}\text{S}$ ) from October 1964 to February 1968. Fluctuations in the polarisation angle of the received signals show the amplitude of small-scale variations in the electron content along the ray path. Results from 12,000 transits are used to map the changes occurring over much of the Antarctic ionosphere. In equinox there is a large diurnal variation with a maximum near local sunset. There is no overall diurnal change in summer, at sunspot minimum, although the density of irregularities is reduced near 05.00 and 18.00 local time. The winter results are similar except for an additional production of irregularities throughout most of the Antarctic near 04.00 U.T. (corresponding to local noon near the corrected geomagnetic pole). At sunspot maximum the degree of irregularity increases considerably in all seasons, and shows a definite peak near 06.00 U.T. in agreement with F-region and electron precipitation observations.

In the polar cap zone, at geomagnetic latitudes greater than  $80^{\circ}$ , the degree of irregularity shows a large diurnal variation in summer and winter (but not in equinox) with a maximum near sunset. The polar peak shows at latitudes near  $80^{\circ}$  as an increase in the degree of irregularity from 03.00 to 15.00 local geomagnetic time in summer, and 07.00 to 17.00 in winter. Averaged over the whole of the observed area the ionosphere is most irregular about 12 hr before a maximum in magnetic activity. The degree of irregularity then decreases, reaching a minimum about 1 day after the maximum magnetic activity and returning to normal in a further 3 days.

#### 4.6 *Future work.*

About 25,000 transits of the Ionosphere Beacon satellite were recorded at Scott Base. Analysis of the polarimeter plots to determine the total electron content of the ionosphere is complex and could not be automated. This work is now finished, however, and maps showing the variations of electron content over much of the polar cap under summer, winter, solar maximum and solar minimum conditions will be published in 1974. The relation of individual measurements (electron content and irregularity state) to magnetic disturbances will be a continuing study for many years. Using the NNSS satellites a new series of measurements is planned at Siple ( $76^{\circ}\text{S}$ ,  $84^{\circ}\text{W}$ ), Scott Base ( $78^{\circ}\text{S}$ ,  $167^{\circ}\text{E}$ ) and Campbell Island ( $52^{\circ}\text{S}$ ,  $169^{\circ}\text{E}$ ). With both Faraday rotation and Doppler measurements, on magnetic tape, it is hoped that much of the total content analysis can be computerised. An improved diurnal coverage will be obtained with five satellites, and this program should provide a valuable addition to the International Magnetospheric Survey in 1976-78. Siple and Campbell Island are both near  $L = 4$ , although at different geographic latitudes, and are particularly well placed for studies of the plasmapause. Measurements from Scott Base cover a contiguous area extending inside the auroral zone and including the geographic, geomagnetic and dip poles.

### 5. THE FARADAY ROTATION OF SATELLITE SIGNALS.

#### 5.1 *Resolution of the ambiguity in Faraday rotation measurements on beacon satellites (paper 32, November 1970).*

A graphical procedure which had been suggested for reducing the ambiguity in Faraday rotation measurements is shown to be mathematically unsound. The results obtained are useful in some cases, however, because of an implied relation between the mean gradient and the curvature of the total content variation. This physical requirement can be given a simple mathematical formulation. As a special case, this gives a greatly simplified procedure for the commonly assumed case of an overall linear variation.

#### 5.2 *Second order effects in the Faraday rotation of satellite signals (paper 30, May 1970).*

A simple derivation of the second-order Faraday rotation relation is given that shows the contribution of the different effects. A rapid ray tracing program is used to evaluate the errors in first- and second-order relations, and these are plotted under a variety of conditions. A modified form of the second-order relation is suggested to reduce the errors. Magnetoionic path splitting does not affect the Faraday rotation to the third order. The only significant errors are those caused by the high-frequency approximation and by refraction. The first of these is almost independent of zenith angle. The second is zero for magnetically east-west propagation, when accurate results can be obtained to very large zenith angles. The ratio of the Faraday fading rates on 20 and 40 MHz, near the center of the transit, can be used to determine the critical frequency of the ionosphere to within 1 MHz.

### 5.3 *Fast Faraday fading of long range satellite signals* (paper 37, May 1971).

20 MHz radio signals have been received during the day from the satellite Beacon-B when it was below the optical horizon by using a bank of narrow filters to improve the signal to noise ratio. The Faraday fading rate becomes constant, under these conditions, at a level determined by the plasma frequency just below the  $F$ -layer peak. Variations in the Faraday fading rate reveal fluctuations in the electron density near the peak, while the rate of attaining the constant level depends on the shape of the electron density profile.

### 5.4 *The Faraday rotation of satellite signals across the transverse region* (paper 31, November 1970).

The plane of polarization of a high-frequency radio wave rotates on passing through the ionosphere. The rotation is in one direction above the transverse point, and in the opposite direction below. In general, however, the rotation angle is reflected across the transverse region, giving a change of sign. The total rotation is then equal to the sum of the absolute rotations in each section. This does not pass through zero during a satellite transit, but has a minimum value (of several rotations) when the transverse point is near the center of the ionosphere. The sign of the total rotation undergoes a sudden jump when the transverse point is in the lower ionosphere, at a height of 110-220 km (day) or 200-300 km (night). A second jump occurs when the transverse point is in the topside ionosphere. Between these two times, a clockwise rotation of the transmitting antenna appears as an anti-clockwise rotation at the ground, and the measured Faraday rotation differs from the expected value by  $90^\circ$  (for the Beacon satellites).

### 5.5 *The conditions for coupling of ordinary and extraordinary rays in the ionosphere* (paper 33, December 1970).

The effect of coupling between the ordinary ( $O$ ) and extraordinary ( $E$ ) components is examined using the coupled wave equations. The coupling in any region is said to be critical when, for initial  $O$  and  $E$  modes of equal amplitude, the relative phase of the  $O$  and  $E$  modes emerging from the region is constant and independent of the initial phase. Under these conditions a pure  $O$  (or  $E$ ) wave entering the coupling region emerges as  $O$  and  $E$  components of equal amplitude. When coupling is greater than the critical value, an increasing phase difference between the initial  $O$  and  $E$  components becomes a decreasing phase difference after passage through the coupling region. This change produces a reversal in the sign of the Faraday rotation. For a constant value of the coupling ratio  $Q$ , critical coupling can occur only if  $Q > 1$  over an appreciable distance. When coupling is caused by a steady change in the angle  $\theta$  between the wave normal and the magnetic field, the overall effect depends only on the peak value of  $Q$  (at  $\theta = 90^\circ$ ).

### 5.6 *The effect of mode coupling on H.F. waves propagated through the ionosphere* (paper 34, December 1970).

Coupling of the ordinary ( $O$ ) and extraordinary ( $E$ ) modes in the ionosphere occurs when the angle  $\theta$  between the wave normal and the magnetic field varies along the ray path. The degree of coupling is specified by a coupling ratio  $Q$ . This reaches a maximum at the transverse point ( $\theta = 90^\circ$ ) and coupling is generally confined to a limited region near this point. The overall effect of this coupling region is evaluated using the coupled wave equations. If the peak value of  $Q(Q_m)$ , at  $\theta = 90^\circ$  is greater than 2.3, the

Faraday rotation of a signal traversing the coupling region is approximately zero. If  $Q_m < 2.3$  the polarisation ellipse is reversed at  $\theta = 90^\circ$  and the absolute number of Faraday rotations increases throughout the ray path. The coupling then causes a slight increase in the amount of Faraday rotation.

Curves are given showing the variation of  $Q$  with height in the ionosphere and with zenith angle, for different directions of propagation at latitudes of  $2-40^\circ$ . The value of  $Q_m$  is primarily a function of height. For a typical F-layer with a penetration frequency of 10 MHz and a wave frequency of 40 MHz,  $Q > 2.3$  only for heights above 500 km or below 200 km at all latitudes. The effect on the Faraday rotation of satellite signals is calculated, using full-wave theory.

#### 5.7 *The meaning of ionospheric electron content as obtained from the Faraday rotation of geostationary satellite signals (paper 38, June 1971).*

Calculations using a wide range of model ionospheres (with a peak at 300 km) show that the integrated electron content up to the height of the satellite could be up to four times the value deduced from Faraday rotation measurements. However, using a fixed mean field height of 400 km, the observed Faraday rotation gives the electron content up to a height  $h_F$  of 2000 km with an accuracy of  $\pm 3$  per cent. For observations at different magnetic and geographic latitudes, and geostationary satellites at different longitudes, the optimum value of  $h_F$  varies by only  $\pm 200$  km. Night-time increases in the height of the ionosphere have little effect on  $h_F$ , but increase the mean field height to about 470 km. Using a fixed value of 420 km, with  $h_F = 2000$  km, gives an accuracy of  $\pm 5$  per cent under most conditions.

#### 5.8 *Future work.*

Measurements of the Faraday rotation of geostationary satellite signals provide a uniquely simple, accurate and continuous monitor of the overall state of the ionosphere. It is intended to continue these measurements indefinitely, as a basis for all future ionospheric studies. The rotating polarimeter is being improved by using phase lock techniques, and results are now recorded in digital form at 10 second intervals. The main use of these records will be in conjunction with other ionospheric measurements to gain an understanding of basic ionospheric physics, as discussed in sections 6.8 and 7.6. Simultaneous digital records of Faraday rotation and differential Doppler shift, using the NNSS satellites, will permit more detailed studies of second order effects and the changes occurring at different heights in the ionosphere.

## 6. STUDIES OF THE IONOSPHERE.

### 6.1 *Variations in electron content after a high altitude nuclear explosion (paper 2, October 1962).*

From measurements of the amplitude of the 54 MHz signal from the satellite Transit 4A, the total electron content of the ionosphere up to a height of 920 km is calculated. Thirty-five minutes after the high-altitude explosion the electron content over Auckland was twice the normal value of  $4.2 \times 10^{16}$  electrons per  $m^2$ . South of Auckland, over Nelson, the electron content increased to about three times the normal value. The Faraday fading of the signals almost completely disappeared north of Auckland, and this effect cannot be explained by normal ionospheric absorption of the extraordinary component.

### 6.2 *The electron content of the low latitude ionosphere (paper 28, January 1969).*

The electron content of the ionosphere was determined at latitudes of  $5^{\circ}\text{S}$  to  $35^{\circ}\text{S}$ , during 354 transits of the satellite S-66 recorded at Rarotonga. In Winter the peak of the equatorial anomaly forms between 0700 and 0900 LT. It remains at a latitude of  $8^{\circ}\text{S}$  throughout the day, and decays slowly overnight. In Summer the peak forms between 0830 and 1030 LT, at a latitude of  $10^{\circ}\text{S}$ . It moves to  $17^{\circ}\text{S}$  by 1400 LT, returning to  $10^{\circ}\text{S}$  as it disappears near sunset. The size of the peak is about the same in both seasons, although the electron content has a seasonal variation of 3:1 at higher latitudes. There is a sharp transition from the approximately constant electron content at medium latitudes to the rapidly increasing content near the equatorial zone. This transition point is at about  $21^{\circ}\text{S}$  in Winter, and  $23^{\circ}\text{S}$  in Summer.

### 6.3 *Continuous records of the total electron content of the ionosphere (paper 11, May 1966).*

Equipment is described for automatic recording of the polarisation angle of the 137 MHz signal from the geostationary satellite Syncom 3. Clear, unambiguous records are obtained from a weak signal, with a time resolution of about 10 sec. The records can be scaled to read directly in terms of the total electron content of the ionosphere ( $N_T$ ). A long-term (relative) accuracy of better than 1 per cent is easily obtained, while rapid changes of only 0.1 per cent in  $N_T$  can be observed.

Results obtained at Auckland from June 1965 to April 1966 are presented. Ionospheric irregularities cause fluctuations of up to 10 per cent in  $N_T$ , while the day-to-day variations in  $N_T$  are 20 per cent less than the changes in the peak density  $N_m$ . Monthly median curves show a diurnal range of about 2.5:1 in winter and 3:1 in summer; less than half as large as corresponding results from the northern hemisphere. A sudden change from winter to summer conditions suggests that the symmetrical equinox form of the upper atmosphere is unstable. Measurements at sunrise give an integrated production rate for an overhead Sun of  $0.9 (\pm 0.2) \times 10^{14}$  electrons  $m^{-2} \text{ sec}^{-1}$ . This agrees with results obtained from ionograms if the loss coefficient in the F1-region is  $10^{-14} m^3 \text{ sec}^{-1}$ . Measurements at sunset give an effective recombination coefficient  $\beta'$  of  $1.2 \times 10^{-4} \text{ sec}^{-1}$  in winter and  $0.5 \times 10^{-4} \text{ sec}^{-1}$  in summer. These figures agree with observations of the rate of change of the critical frequency, showing that the ionisation decays at the same rate at all heights.



#### 6.4 *Changes in the topside ionosphere after a large magnetic storm (paper 15, December 1966).*

Continuous records of the total electron content of the ionosphere, obtained using signals from a geostationary satellite, are used to study the changes occurring during a large magnetic storm at midwinter, sunspot minimum (15-18 June, 1965). The results are compared with those obtained from a full analysis of ionograms taken at 15-min intervals over a period of 14 days. The peak density and the sub-peak content showed the usual small, irregular variations. The changes in total content and in slab thickness were, however, large and systematic with a significance level exceeding 99.99%. This suggests that total content measurements may give a much clearer picture of storm morphology.

The mean scale height gradient  $\Gamma$  above the peak of the  $F$ -layer was calculated from the topside electron content and the scale height at the peak. There was an initial increase in  $\Gamma$ , from 0.2 to 0.4, caused by heating of the topside ionosphere or a sustained influx of electrons. At the peak of the storm  $\Gamma$  dropped to 0.03, showing that the scale height increased very slowly above the peak. This requires an increased mixing of the ionosphere to reduce the normal diffusive separation. The gradual recovery to normal values of scale height took 5 days. Calculations of the integrated loss rate also showed an increased mixing, giving more neutral molecules in the  $F$ -region, which persisted for 5 days.

#### 6.5 *Night-time changes in the electron content of the ionosphere (paper 19, October 1967).*

The total electron content of the ionosphere was determined at Auckland ( $37^{\circ}\text{S}$ ) and at Invercargill ( $46^{\circ}\text{S}$ ) throughout each night from June 1965 to December 1966. Increases in total content were observed on nearly half the nights in winter but not in summer. Comparison with northern hemisphere results shows that this is a true seasonal change. A model assuming a constant source of ionization and a fixed loss rate was fitted to the measurements by a least-squares analysis. This showed that a nighttime influx of ionization also occurs in summer, although the increased density makes its effects less obvious. The influx is reduced at low latitudes and, possibly, at the equinoxes. Increases in magnetic activity have little effect on the night-time source of ionization, but cause an increase in the recombination coefficient.

#### 6.6 *The maintenance of the night-time ionosphere (paper 21, January 1968).*

The electron content of the ionosphere was recorded continuously at latitudes of  $34^{\circ}\text{S}$  and  $42^{\circ}\text{S}$  for a period of 18 months. The results are combined with ionosonde measurements to determine the mean changes in the night-time ionosphere at latitudes of  $10$  to  $60^{\circ}$ . The effective loss coefficient  $\beta$  is constant at about  $4 \cdot 10^{-5} \text{ sec}^{-1}$  in summer, and  $3 \cdot 10^{-5} \text{ sec}^{-1}$  in winter, throughout most of the night. This agrees with the values observed at sunset when allowance is made for changes in the height and temperature of the  $F$ -layer.

A nocturnal source of ionization is observed at all seasons. It acts for about 3 hr near midnight, at geomagnetic latitudes of  $15$  to  $40^{\circ}$  in summer and  $25$  to  $50^{\circ}$  in winter. The total influx is about  $2 \cdot 10^{16} \text{ electrons/m}^2$ , with an annual variation of 50 per cent and a solar cycle variation of 150 per cent. The influx increases by 50 per cent during periods of high magnetic activity.

Calculations of the diffusion of ionization from the exposure, assuming that there is no production or loss of protons by charge exchange, predict a nocturnal flux of  $2.10^{16}$  electrons/m<sup>2</sup> into the ionosphere at latitudes between 20 and 45°. This influx will extend to higher latitudes in winter than in summer. It will have an annual variation of 50 per cent and a solar cycle variation of about 150 per cent.

#### 6.7 *The electron content of the southern mid-latitude ionosphere* (paper 42, October 1971).

Hourly values of the electron content of the ionosphere ( $I$ ), from June 1965 to August 1971, are used to define the mean diurnal, seasonal and solar cycle effects at latitudes of 34°S and 42°S. The diurnal ratio ( $I_{\max}/I_{\min}$ ) is about 3 in summer and 4 in winter, compared with 4-6 in the northern hemisphere and 20 at the dip equator. The electron content shows a peak near 19 hr in summer caused by upwards movements. The corresponding peak in  $N_m$  is delayed to 22 hr at solar maximum, by thermal contraction of the ionosphere. There is no seasonal anomaly at 34°S. The major anomaly is a large peak in April; at 42°S  $I$  increases by 70 per cent (and  $N_m$  by 100 per cent) in 40 days at the March equinox. Changes with solar flux  $S^m$  show  $I \propto S - 20$  for summer day, summer night and winter day. Winter night values are almost constant because of a lowering of the  $O^+/H^+$  transition height to 450 km near solar minimum. The associated changes in atmospheric composition appear to lag at least 6 months behind the changes in  $S$ . 27-day variations in  $I$  follow changes in  $S$ , with a lag of  $1.0 \pm 0.1$  days, and give values of  $dI/dS$  about 35 per cent less than for the solar cycle changes. Large day to day variations in  $I$  at periods of less than 10 days are attributed to changes in the loss rate. The per cent variation is approximately independent of season and solar activity, but increases at night in winter.

#### 6.8 *Future work.*

A considerable amount of information has been gathered on the response of the ionosphere to magnetic activity. Detailed studies of the changes in electron content and in bottomside  $N(h)$  profiles have been carried out for 9 major and 30 minor storms. Correlation studies over half a solar cycle have shown the overall response of the ionosphere to magnetic activity, and these results should be compiled next year. The electron content variations are interpreted in terms of changes in the temperature, recombination coefficient and movement of the ionosphere. The availability of topside sounder records over New Zealand will be of considerable help in the future, for separating the different effects. A system for routine analysis of topside ionograms, using an on-line computer, has been established. Mathematical models of topside profiles, including the effects of varying temperature, ion composition and vertical fluxes, have been developed in a form suitable for fitting to experimental profiles. Application of this procedure to 60,000 Alouette 1 profiles (at Ottawa) showed its reliability. It is hoped that, using topside profiles to provide periodic calibrations, the continuous electron content records can be used to give a more detailed picture of changes in the upper ionosphere and exosphere.

## 7. THE EXOSPHERE AND NEUTRAL ATMOSPHERE

### 7.1 *Calculations of diurnal changes in the exosphere* (paper 20, January 1968).

Explorer 22 measurements of the electron density and temperature at a height of 1,000 km at night, are used to calculate the total electron content of the tubes of force at different latitudes. The results agree with whistler measurements if the ion composition changes from at least 50%  $H^+$  at latitudes below  $30^\circ$ , to about 5%  $H^+$  at latitudes above  $60^\circ$ . The tube content is then approximately constant at  $10^{17}$  electrons/m<sup>2</sup> between latitudes of  $30$  and  $50^\circ$ , with a rapid decrease at lower latitudes and a rapid increase at higher latitudes.

Diurnal changes are calculated assuming that there is no change in the total proton content of a tube of force. Diurnal changes in the ionosphere then produce a variation in the  $O^+$  to  $H^+$  transition level, at medium latitudes, from 500 km at night to 1000 km during the day. This agrees with recent observations. The calculated diurnal change in the density above the Equator is consistent with whistler results. The diurnal change at 1000 km disappears at latitudes between  $20$  and  $50^\circ$ , agreeing with Explorer 22 and Alouette I observations. There is a downwards flow of ionization at night, of an amount almost sufficient to maintain the night ionosphere at latitudes between  $20$  and  $45^\circ$ .

### 7.2 *The semiannual change in exospheric temperature* (paper 39, September 1971).

Satellite drag measurements show a regular semiannual change in the density of the upper atmosphere. This was originally interpreted as a change in temperature, through about 20%, with maxima just after the equinoxes. In 1971 it was suggested that the change may not be primarily a temperature effect. Measurements at Auckland over a period of 3 years show, however, a regular semiannual change in the slab thickness of the ionosphere. This could not result purely from changes in density, but shows a regular change of 20% in temperature agreeing closely with the satellite drag result.

### 7.3 *Results obtained from measurements of the slab thickness of the ionosphere* (paper 43, December 1971).

The thickness of the peak of the ionosphere depends on the temperature  $T_n$  of the neutral gas (not on the plasma temperature  $T_p$ , as is often supposed). The peak corresponds approximately to an  $\alpha$ -Chapman layer at a temperature of  $0.87T_n$ . Calculations of the Faraday rotation of satellite signals passing through this layer show that the apparent slab thickness is given by  $\tau = 0.22T_n + 7$  km.

Expansion of the topside ionosphere increases  $\tau$  by about 13 km during the day in summer. Changes in the E and F1 regions increase  $\tau$  by 7 km during the day in summer and decrease  $\tau$  by 5 km in winter. Vertical drifts caused by neutral winds have little effect. A vertical flux of ionisation, about 20% of the limiting value, will decrease  $\tau$  by 5 to 10% for a few hours after sunrise in winter. Near solar minimum  $\tau$  is increased by a lowering of the  $O^+/H^+$  transition height  $h_T$ . If the neutral temperature  $T_n$  is estimated,  $h_T$  can be determined from measured values of  $\tau$  using the relation  $h_T = 0.85T_n - 0.258T_n \log_{10} [\tau - (.22T_n + 7)] + 250$  km.

Hourly values of slab thickness were determined over a period of 6 years at  $34^{\circ}\text{S}$  and  $42^{\circ}\text{S}$ . Near solar maximum the nighttime values were about 260 km in all seasons. The corresponding neutral temperatures agree with satellite drag values; they show a semi-annual variation of 14% and a seasonal change of 5%. Daytime values of  $\tau$  were about 230 km in winter and 320 km in summer. The seasonal change is caused by an increase of 25% in the neutral temperature, 6% from increased plasma temperatures in the topside ionosphere, and 6% from changes in the  $E$  and  $F1$  regions. Temperatures increase steadily throughout the day (at  $22^{\circ}/\text{hr}$  near solar maximum and  $11^{\circ}/\text{hr}$  near solar minimum) in all seasons, with a rapid post-sunset cooling in summer. This agrees with incoherent backscatter results.

Near solar minimum increases in  $\tau$  show a reduction of the  $\text{O}^+/\text{H}^+$  transition height to 700 km throughout the day in summer, and to 570 km near noon and 420 km near midnight in winter. Fluctuations near sunrise show departures from diffusive equilibrium. A peak at 06 hr in winter is caused by a reduction in  $N_m$  when the meridional winds reverse and the layer descends. A large upwards flux, equal to about 30% of the maximum (limiting) value, reduces  $\tau$  for several hours after sunrise in winter.

#### 7.4 *Seasonal and diurnal changes in exospheric temperature and composition, from ionospheric slab thickness measurements (paper 44, January 1973).*

Routine measurements of the slab thickness of the ionosphere, from 1965 to 1971, are used to infer the changes in neutral temperature and ion composition at a mean latitude of  $40^{\circ}\text{S}$ . Values of neutral temperature  $T_n$ , at solar maximum, are 5-10% above northern hemisphere backscatter results. The diurnal and seasonal changes agree closely with satellite drag and backscatter measurements, except that the maximum temperature occurs after sunset in winter. Winter nighttime values of the  $\text{O}^+/\text{H}^+$  transition height  $h_T$  were 500 km in 1965-66, 800 km in 1968-1969 and 700 km in 1971. Changes in  $h_T$  lag about 6 months behind the changes in solar flux. Diurnal variations have a minimum just before sunrise and a maximum 1 to 3 hr after noon. On winter nights  $h_T$  descends to the level set by chemical equilibrium. On summer nights  $h_T$  is always above this level, giving a continual production of  $\text{H}^+$  which serves as an additional source for maintaining the nighttime ionosphere in the winter hemisphere.

#### 7.5 *Changes in atmospheric composition inferred from ionospheric production rates (paper 47, June 1973).*

Changes in the total electron content of the ionosphere near sunrise are used to determine the integrated production rate in the ionosphere ( $Q$ ) from 1965 to 1971, at latitudes of  $34^{\circ}\text{S}$ ,  $20^{\circ}\text{N}$  and  $34^{\circ}\text{N}$ . The solar cycle change is given approximately by  $Q \propto S-20$ , where  $S$  is the 10.7 cm solar flux. All stations show a regular semiannual variation in  $Q$ , through a range of 1.3:1. This is interpreted as an increase in the ratio  $\text{O}/\text{N}_2$  (the relative densities of atomic oxygen and molecular nitrogen) near the equinoxes. Northern hemisphere values of  $Q$  are nearly twice as large as southern hemisphere results, requiring an increase of about 3 times in the ratio  $\text{O}/\text{N}_2$  in the northern hemisphere. This ratio decreases in summer, near solar maximum, giving the well-known seasonal anomaly in the ionosphere. The seasonal change is larger at  $34^{\circ}\text{N}$  than at  $20^{\circ}\text{N}$ , and is completely absent at  $34^{\circ}\text{S}$ . Measurements of the time at which sunrise production begins confirm that the absorption of solar radiation is primarily by  $\text{N}_2$  at all times at  $34^{\circ}\text{S}$ , but changes from  $\text{N}_2$  in summer to atomic oxygen in winter in the northern hemisphere near solar maximum.

## 7.6 *Future work.*

The effective slab thickness of the ionosphere can readily be monitored on a cheap, routine basis. Work at Auckland has established that the results are closely related to the neutral exospheric temperature, and the occurrence of  $H^+$  ions. Ionospheric measurements will therefore be increasingly used to observe changes in temperature and composition of the neutral atmosphere. Checks on the reliability of this work will be possible using the topside sounder measurements now available over New Zealand (as outlined in section 6.8). The assumptions involved in obtaining exospheric temperature and composition from slab thickness measurements are no more alarming than those made, at a similar stage of development, in the interpretation of incoherent scatter measurements. Continued theoretical and experimental work in this field should therefore provide valuable data for comparison with the northern hemisphere backscatter installations, to provide more information on the important inter-hemisphere differences which appear to exist. As understanding of ionospheric process develops measurements of integrated production and loss rates, at different times of day, should also provide new information on neutral composition (as in 7.5) and the effect of neutral winds.

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